

# Improved Fidelity for Calculating Attenuation Through Obscurants

By

*Scarlett D. Ayres*

U.S. Army Research Laboratory

Survivability Lethality Analysis Directorate

White Sands Missile Range, NM 88002

505-678-4350, **Error! Bookmark not defined.**

## Abstract

Assessing the impact of obscurants on performance is a very complex issue. Atmospheric propagation through obscurants can effect acquisition by the U.S. missiles. This report describes a technique, as well as models used to simulate and analyze battlefield scenes in the wavelength of interest using the Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) model. Most analysis of obscurant effects on battlefield sensors have focused on using a single band-averaged mass extinction coefficient to represent the obscurant's ability to degrade the Line of Sight (LOS). This mass extinction coefficient when combined with the Concentration Length (CL) yields a single number for the transmittance over the wavelength band. The extinction for several wavelength bands are modeled in COMBIC. Project managers have expressed an interest in the spectral attenuation (the variation of the attenuation due to variation in the mass extinction coefficient sometimes referred to as "complex" attenuation by the user) over the band-pass specific to their sensor. An aerosol code has been used to model the variation of mass extinction coefficient with wavelength. The COMBIC CL data can then be combined with the wavelength-dependent extinction coefficient to determine the spectral attenuation over the specific band-pass for the sensor. This represents a significant improvement in the use of COMBIC over using a single number for attenuation to represent a "canned band-pass". The spectral attenuation is used in this report to describe the variation in apparent emissivities for some naturally occurring materials. Analysis shows that the range of the transmitted emissivity for a tree leaf at 8 – 14 microns through White Phosphorus smoke at moderate CL values is .28. The range in emissivity for tree leaf without smoke is .02. The aerosol code is used to compare the band-averaged WP mass extinction coefficient with COMBIC values. Excellent agreement is obtained with a root-mean-square of less than 7% for the visual and 1.54 microns. Therefore, the aerosol code is used to compute the coefficients for the extinction equation used by COMBIC to compute variation of extinction with relative humidity for at .3 microns and 1.54 microns.

## 1. Introduction

The Broadband Integrated Transmittances (BITS) model was developed by the (then) U.S. Army Atmospheric Sciences Laboratory to numerically calculate broadband transmittances (Davis et al, 1990). This model is located in the Electro-Optical Atmospheric Effects Library (EOSAEL). The BITS model includes spectral effects of the atmosphere, detectors, filters, optical surface, targets, and obscurants on broadband transmittances. The BITS model allows the user to input the spectral response of the detector and filters into the model as spectral response-wavelength pairs. However, most project managers of target acquisition systems, have their own in-house system performance model. SLAD has been requested by the Stinger project office to provide spectral attenuation for use in just such a model. An

option to access a file containing the variation in extinction to compute the spectral attenuation over a band-pass specified by the user has been added to the model.

Davis, Berrick and Gillespie in 1990, performed a comparative study between the Beer's law calculation and band-integrated calculations of WP smoke for ASL SMART transmissometer using the BITS model. To simplify the analysis, the target spectral signature and the system optics were assumed to be wavelength independent and have been set to unity. They found that large differences between predicted transmittances using an averaged extinction coefficient when compared to spectral extinction can occur. These differences for the conditions modeled can be important below transmittance of .1, the range in which threshold of detection becomes critical for most sensors.

Sutherland, Yee, Fernandez and Millard also made a comparison study in 1996 for various types of fog. They modeled the mass extinction coefficient as a constant mean component and a wavelength dependent component. The received signal can be considered as being composed of a wavelength independent part multiplied by a correction factor. They found that the correction factor is nearly one for advective fog where the mass extinction coefficient is nearly independent of wavelength. For other types of fog like artificial fog and radiative, there is increasing departure of the correction factor from one with increasing CL. Though, the correction factor can be ignored except for very high CL values.

It is convenient to also use a band-averaged emissivity to describe the background for infrared scenarios. The emissivity is defined as the ratio of radiant emittance of the surface to the radiant emittance of a blackbody at the same temperature. Most IR scene generation models use band-averaged emissivities. For some backgrounds, the emissivity is nearly constant. However, other backgrounds exhibit some variation in the emissivity with wavelength. The addition of an obscurant that exhibits variation in extinction over the wavelength band causes the apparent emissivity to vary further. This reports shows how the apparent emissivities for several backgrounds vary in the presence of White Phosphorus for different CLs.

With the recent emergence of the eyesafe laser, the Combined Arms Strategic Task Force Evaluation Model (CASTFOREM) needed the capability to model obscuration effects on these sensors. Phosphorus-based smokes are found in most country's inventory. CASTFOREM models these smokes using the COMBIC model. However, the default tables in COMBIC do not contain extinction at 1.54 microns for WP. The effectiveness of these smokes is dependent on the ambient relative humidity. COMBIC uses a fourth-order extinction equation to compute the extinction. The coefficients of this equation are dependent upon the wavelength and the type of smoke. The Aerosol-Hygroscopic code was used to help determine these coefficients. These coefficients are also determined for the ultraviolet (UV) wavelengths of .3 microns. Several systems such as Stinger use a UV sensor in addition to another wavelength to help discriminate targets from false targets. The Aerosol-Hygroscopic code is used partly because a dearth of actual measured extinction data for WP at 1.54 microns and UV wavelengths exists.

## **2. Models**

### **2.1 COMBIC**

The COMBIC computer simulation predicts spatial and temporal variation in transmission produced by various munitions and vehicles. COMBIC models the effects of reduction in electromagnetic energy

(visible through infrared (IR) wavelengths) by combining the munition characteristics with meteorological information of an idealized real world. It produces transmission histories at any of seven wavelength bands for a potentially unlimited number of sources and lines of sight (LOS). The extinctions for the seven wavelengths for twenty obscurants are included in the model. COMBIC also has the capability of modeling the variation of extinction with wavelength for hygroscopic smokes like WP (Ayres and DeSutter, 1993). Path-integrated concentration is determined for each observer (seeker)-target pair, and transmittance are computed at each of seven wavelength bands for (in principle) any scenario which is defined by multiple sources and active LOS.

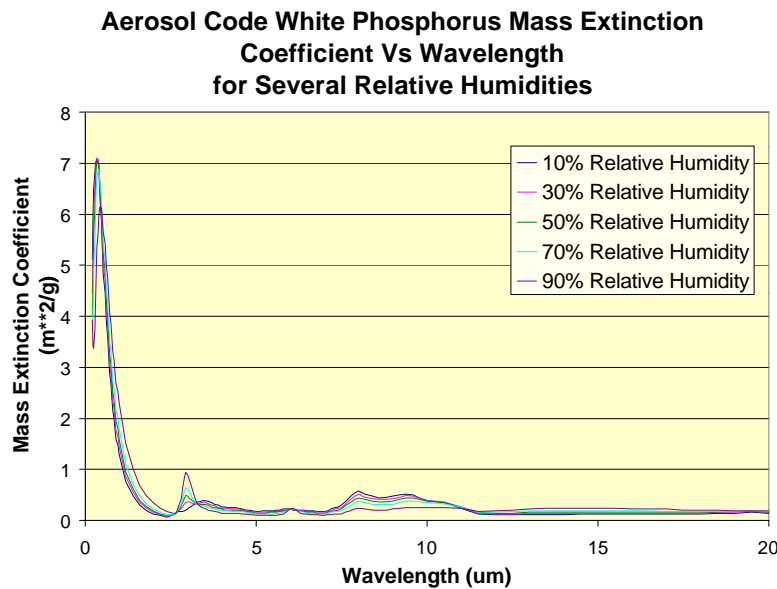
## 2.2 Aerosol-Hygroscopic Code

The mass extinction coefficient is a wavelength-dependent optical property of the obscurant material. It can also depend on the particle size distribution, particle composition, refractive indices, shape and orientation. Most established smokes in the US inventory and modeled by COMBIC's default tables are considered to be spherical. The mass extinction coefficients for many smokes in these default tables are heavily weighted towards measurements rather than theory. COMBIC uses the extinction per unit obscurant concentration integrated over the entire size distribution of airborne particles. The model also uses a band-averaged mass extinction coefficient for wavelength bands .4 - .7 microns, .7 - 1.2 microns, 3 - 5 microns, and 8 - 12 microns. The extinction coefficient in COMBIC accounts for scattering of radiation out of the path of propagation and absorption of radiation along the path of propagation.

White Phosphorus and Red Phosphorus burn to produce a hygroscopic smoke containing phosphoric acids. The extinction for these smokes is primarily due to scattering in the visible and absorption in the infrared (IR). These smokes are composed of spherical liquid particles that grow with relative humidity to an equilibrium size by absorbing ambient moisture that depends on the ambient relative humidity. The mass extinction varies significantly with relative humidity. Theory is needed to supplement measurements to compute the extinction variation for the various wavelengths over all relative humidities. Extinction of airborne aerosol ( $m^2/g$ ) depends on four factors: (1) the index of refraction of the obscurant; (2) the distribution of particle sizes; (3) shape and orientation of particles; and for hygroscopic smokes; (4) the effect of dilution by water absorbed from the air on mass, size distribution and effective refractive index (Hooek and Sutherland, 1993). White Phosphorus smoke can be modeled as spheres allowing the use of the Mie theory.

The Mie theory provides exact computation of absorption, scattering and extinction coefficients for an individual, homogeneous sphere based upon the particle radius, mass density and refractive index. The problem is that most aerosols have particles that range in size. Choosing an appropriate size distribution can effect results. Furthermore, hygroscopic smoke particle size distribution and indices of refraction change concurrently with relative humidity. The difficulty is to compute the extinction of the composite smoke particle. The Aerosol-Hygroscopic Code produced by Klett and Sutherland, 1988, is based upon the Mie theory and utilizes a lognormal particle distribution. The geometric mean radius and the geometric mean standard deviation  $\sigma$  characterize this distribution. The model uses the refractive indices for water and WP, combined with lognormal particle size distribution dependent upon relative humidity to compute the mass extinction coefficients vs. wavelength for any desired relative humidity. Though the refractive indices for water are well known, the indices for the composite smoke particle must be modeled with mixing rules. The Aerosol-Hygroscopic model uses the rule of volumetric additivity of dielectric constants (Newton's rule) as the mixing rule.

Figure 1 shows the mass extinction coefficient for various relative humidities using Kletts and Sutherland's (1988) Aerosol-Hygroscopic Code. The mass extinction coefficient in the visible region actually decreases at high relative humidities. This is due to the particle size distribution shift to larger radii with the absorption of moisture and the resultant decrease in refractive index. Water vapor is the strongest absorber for clear air in the 8 – 12 microns. Klett and Sutherland found that vapor depletion in the aerosol could be ignored except for high CL. Note, that the refractive indices for WP peak in the 8 - 12 microns wavelength band. The Aerosol-Hygroscopic Code is used in this effort to compute the extinction at .3 and 1.54 microns and to compute the spectral extinction coefficient.



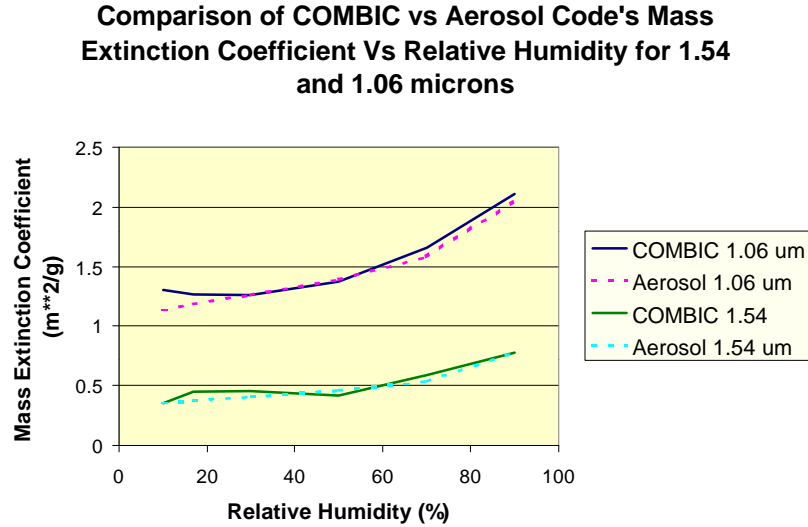
**Figure 1 The variation of the White Phosphorus mass extinction coefficient vs wavelength shown for 10%, 30%, 50%, 70% and 90 relative humidities**

### 3. Near IR (1.54 μm)

Laser rangefinders measure the time-of-flight of a short pulse of laser light to and from a target. This time of flight is then converted to a range, which is displayed in the rangefinder's sighting optics. Most laser rangefinders are not eyesafe. This limits their use in training and provides safety concerns in the field. Many of these lasers emit a wavelength of 1.064 microns. While invisible to the human eye, this wavelength is not only passed through the eye to the retina, but is also focused by the eye's lens onto the retina. At 1.064 microns the maximum permissible exposure for single pulse lasers is limited to a few microjoules of energy. Hence at the nominal 15mJ operating output levels of some lasers, the potential for eye damage is quite high (Galoff and Sliney, 1990). Neutral density filters were developed that reduced the eye hazard of these lasers but the operational usage of the 1.06-micron lasers was also reduced.

Beyond 1.4 microns, the eye no longer focuses laser energy on the retina and higher energy levels can be tolerated. Several types of lasers were studied that operated at different wavelengths, but the Army eventually settled on a 1.54 micron laser that was eyesafe at the aperture, even when viewed with magnifying optics. Full scale production of the Mini Eyesafe Laser Infrared Observation Set (MELIOS) has started. An unintentional benefit of switching from the 1.06 micron laser to the 1.54 micron laser is that the extinction is significantly reduced. A quick inspection of figure 1 shows that the extinction curve

is quite steep in the near-IR. Assuming that the WP mass extinction coefficient for the 1.54 wavelength and the 1.06 wavelength is the same would introduce errors up to 200% in computing optical depth. In order to compute the 1.54 micron mass extinction coefficient, the Aerosol-Hygroscopic Code was run with varying geometric mean radius and standard deviation  $\sigma$  for 1.06 microns until the best fit with COMBIC produced mass extinction coefficients was obtained.



**Figure 3 White Phosphorus Mass extinction coefficient vs. relative humidity and 1.54 microns computed by COMBIC and the Aerosol-Hygroscopic Code**

COMBIC computes the mass extinction coefficient through the following empirical equation:

$$\alpha(\lambda) = a_1 * RH + a_2 * RH^2 + a_3 * RH^3 + a_4 * RH^4$$

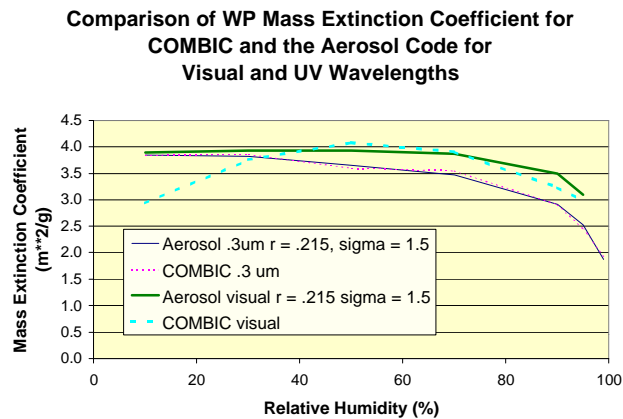
where  $\alpha(\lambda)$  is the mass extinction coefficient for wavelength or wavelength band and RH is the relative humidity. Curve fitting the 1.54 micron data produced by the Aerosol-Hygroscopic Code yields  $a_1 = 5.2782\text{E-}02$ ,  $a_2 = -2.0106\text{E-}03$ ,  $a_3 = 2.9326\text{E-}05$ , and  $a_4 = -1.3817\text{E-}07$ . The correlation coefficient is .962 proving that the derived curve for COMBIC strongly matches the data produced by the Aerosol-Hygroscopic model. Figure 2 shows the mass extinction coefficient vs. relative humidity computed by COMBIC's empirical extinction equation for 1.06 and 1.54 microns and by the Aerosol-Hygroscopic code for 1.06 microns and 1.54 um. Geometric mean radius and sigma used by the Aerosol-Hygroscopic code is  $r = .215$  microns and  $\sigma = 1.2$  microns. Note that the agreement between COMBIC and the Aerosol-Hygroscopic code at 1.06 microns is quite good with a root-mean-square (rms) deviation of 2.85%. Thus, there is a large degree of consistency between COMBIC and the Aerosol-Hygroscopic Code.

## 4. UV Extinction

Currently, COMBIC contains in its default tables, extinction data from visible to far IR. However, some sensors operate in the ultraviolet (UV). Also, UV emissions are considered a missile observable. UV extinction for some non-hygroscopic smokes have been collected elsewhere (Johnston and Rouse 1997).

The coefficients for the extinction equation used by COMBIC is needed for hygroscopic smokes. The same methodology used in computing the coefficients for COMBIC's empirical extinction equation at 1.54 microns is used here. However, the Aerosol-Hygroscopic model is run to compute the mean geometric radius and standard deviation that gives a best match with COMBIC at visual wavelengths. These values are then used in the Aerosol-Hygroscopic model to compute the extinction at .3 microns. Figure 3 shows the mass extinction coefficient vs. relative humidity for .4 - .7 microns and .3 microns produced by the Aerosol-Hygroscopic model and by COMBIC's extinction equation for WP. The geometric radius is .215 microns and geometric standard deviation  $\sigma$  is 1.5 microns. The rms percent difference between the two models for the visual waveband is 6.8. The coefficients for the extinction equation used by COMBIC at UV wavelengths become  $a_1 = 5.2782\text{E-}02$ ,  $a_2 = -2.0106\text{E-}03$ ,  $a_3 = 2.9326\text{E-}05$ , and  $a_4 = -1.3817\text{E-}07$ . A zeroth-order term,  $a_0 = 3.3420$  had to be added in order to obtain the best fit. The correlation coefficient is .997 proving that the derived curve for COMBIC strongly matches the data produced by the Aerosol-Hygroscopic model.

Note that the agreement between COMBIC's extinction equation and the Aerosol-Hygroscopic model for visual wavelengths is fairly good for humidities above 30%. There is increasing discrepancy below 30% relative humidity. One possible source for this discrepancy could be that the indices of refraction for dry WP particulate were extrapolated from "wet" indices. However, the extinction at visual wavelength for WP is believed to be insensitive to the indices. Another possible source of discrepancy is that the extinction at visual wavelengths is *very* sensitive to the particle size distribution. Figure 1 shows the extinction exhibits a marked peak at visual wavelengths. Changing the geometric mean radius or sigma even slightly can have significant effects on the extinction. The values computed by here are believed to be well within the noise of real world values.



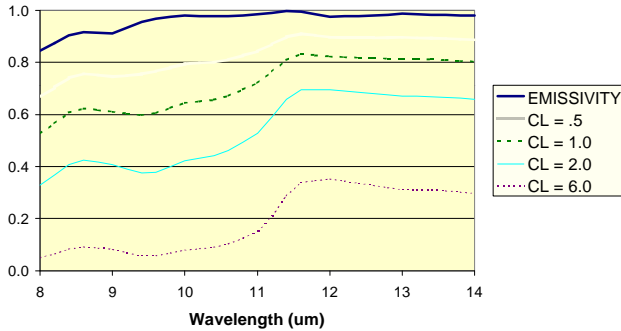
**Figure 4 Comparison of WP mass extinction coefficient for COMBIC and the Aerosol Code for visual and UV wavelengths.**

## 5. Spectral Emissivities of Some Natural Soils and Vegetation

The variation of the mass extinction coefficient can effect the natural emissivity. Figures 4-7 shows the emissivity of red clay, fine sand, coarse sand and a tree leaf for the 8-14 um region (Sutherland, 1986) for clear air (top curve) and for increasing WP CL values. These figures show that the spectral attenuation of WP in this wavelength region adds a spectral dependency to the emissivity that may not be present in clear air. The reason for this variation is that the refractive indices of phosphoric acid droplets vary the

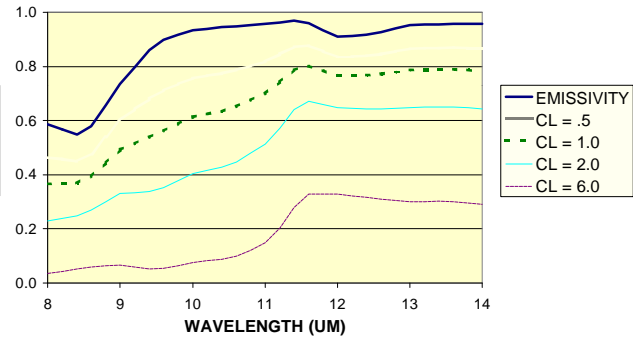
most with relative humidity in the 8 – 12 micron wavelength band (Hoock and Sutherland, 1993). The emissivity for tree leaf was nearly constant over the wavelength band in clear air. For increasing CL values, the figures show that there is an increasing wavelength dependence of the apparent emissivity of a tree leaf for this wavelength region. This is also true for clay and fine sand. The effects of smoke on coarse sand is somewhat different. At increasingly higher CL values the smoke degraded some of the natural variation in emissivity.

**TRANSMITTED EMISSIVITY OF CLAY  
THROUGH WP FOR DIFFERENT CLs**



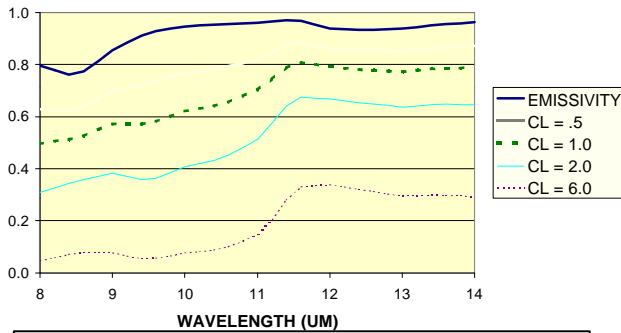
**Figure 4 Emissivity for red clay for 8 - 14 microns**

**TRANSMITTED EMISSIVITY OF COARSE SAND  
THROUGH WP FOR DIFFERENT CLs**



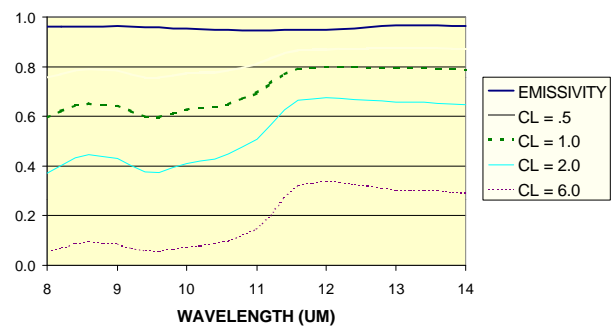
**Figure 5 Emissivity for coarse sand for 8 - 14 microns**

**TRANSMITTED EMISSIVITY OF FINE SAND  
THROUGH WP FOR DIFFERENT CLs**



**Figure 6 Emissivity for fine sand for 8- 14 um**

**TRANSMITTED EMISSIVITY OF TREE LEAF  
THROUGH WP FOR DIFFERENT CLs**



**Figure 7 Emissivity for tree leaf for 8 – 14 microns**

## 6. Conclusion and Future Work

Analysis of the WP mass extinction coefficient computed by the Aerosol-Hygroscopic code shows that it compares very favorably with the extinction coefficient computed by COMBIC at .4 - .7 microns and 1.54 microns. Therefore, the code can be used with confidence to compute the mass extinction coefficient variation with relative humidity at .3 microns and 1.54 microns. The data is curve fitted for each wavelength using a fourth order polynomial for eventual inclusion in COMBIC extinction module for use by CASTFOREM. The correlation coefficient is quite high ( $> .95$ ) between the Aerosol-Hygroscopic code data and the fourth order equation used by COMBIC.

The effect of smoke on natural emissivities is complex. The spectral variation of the backgrounds examined in this report increased with increasing CL except for coarse sand. The effect of smoke on coarse sand is to “wash out” some of the natural variation in spectral emissivity. Analysis shows that the range of the transmitted emissivity for coarse sand at 8 – 14 microns through WP smoke at moderate CL values of 6 g/m<sup>2</sup> is .29. The range in emissivity for coarse sand without smoke is .42.

Future work will include:

- Acquiring data for validation of coefficients of extinction equation for .3 and 1.54 microns
- Add extinction for .3 microns and 1.54 microns to the default tables (CASTFOREM)
- Using COMBIC and the hygroscopic code to compute the spectral attenuation over the bandpass for STINGER.
- Inclusion of sensor effects and aerosol emissivity (Nealon and Sutherland, 1999)

## 7. References

Ayres, S.D., and S. DeSutter, 1993: “Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) Users Guide,” U.S. Army Research Laboratory.

R. E. Davis, S. E. Berrick and P.S. Gillespie; 1990, “Broad-Band Integrated Transmittances: The Bits Module,” Proceedings of the Eleventh Annual EOSAEL/TWI Conference, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico.

Galoff, P. K and D.H. Sliney, 1990: “Laser Safety, Eyesafe Laser Systems, and Laser Eye Protection,” Proceedings for the International Society of Optical Engineering, Vol. **1207**, 112-123, P.O. Box 10, Bellingham, Washington, 98277-0100.

Holst, G. C., 1995: “Electro-Optical Imaging System Performance,” JCD Publishing, 2932 Cove Trail, Winter Park, FL 32789.

Johnston, D. J., W.G. Rouse 1997: “The Vehicle Smoke Protection Model and Cloud Density Visualization Utility, Version 1.1,” OMI-598, 1 Newport Drive, Suite H, Forest Hill, MD 21050.

Hoock, D. W., and R. A. Sutherland, 1993: “Chapter 6 – Obscuration Countermeasures,” The Infrared & Electro-Optical Systems Handbook, Volume 7- Countermeasures, Editor - D. H. Pollock, Environmental Research Institute of Michigan, Ann Arbor Michigan.

Sutherland, R.A., 1986: “Broadband and Spectral Emissivities (2-12  $\mu\text{m}$ ) of Some Natural Soils and Vegetation,” Journal of Atmospheric and Oceanic Technology, Volume 3, No. 1.

Sutherland, R.A., 1988: “Effects of Atmospheric Moisture in Determining Obscurant Optical Properties from Field Data,” Ninth Annual EOSAEL/TWI Conference, Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002.

Sutherland, R.A., Y. P. Yee, G. L. Fernandez, and J.B. Millard, 1996: “Droplet size and transmittance spectra of mechanically generated water fogs,” Atmospheric Research 41: 299-319.



J.F. Nealon and R.A. Sutherland, 1999: "Cloud Contrast Modeling and Validation for Targets", 5<sup>th</sup> Annual JAWS Symposium & Exhibition, San Diego, CA, 14 –18 June, 1999. In Press.